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REFINEMENT OF CASTING TECHNIQUES FOR SMALL AIR-COOLED TURBINE BLADES - PHASE 1A

GENERAL ELECTRIC COMPANY
Aircraft Engine Group
Lynn, Mass. 01910

November 1978

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U. S. ARMY RESEARCH AND TECHNOLOGY LABORATORIES (AVRADCOM)
Fort Eustis, Va. 23604

APPLIED TECHNOLOGY LABORATORY POSITION STATEMENT

This report discusses the current effort in blade casting technology, which is a part of a large thrust at the Applied Technology Laboratory and throughout the Army to improve or refine manufacturing techniques. This program was the outgrowth of combined interest on the part of the Army and Industry to advance manufacturing technology and to reduce the cost of high-performance, small, gas turbine engines.

Mr. Jan M. Lane of the Propulsion Technical Area, Aeronautical Technology Division, was the Project Engineer for this effort.

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The design of the T700 stage-one turbine blade was reevaluated to permit application of advanced coring techniques to investment cast turbine blades. Small cores were machined to produce turbulators within the cored passages and bent to provide serpentine cooling passages. Injection molding of ceramic materials was investigated as a method of reducing the cost of small intricate cores. These techniques resulted in improved use of cooling air, and they can increase blade life or specific fuel consumption over the standard

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20. ABSTRACT (Continued)

configuration.

Design history, manufacturing steps, qualification procedures, and cost analysis are discussed for the Advanced Core Technology blade.

PREFACE

This project was accomplished as part of the U. S. Army Aviation Manufacturing Technology Program. The primary objective of this program was to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in the production of Army material. Applied Technology Laboratory technical direction for this program was provided by Mr. J. M. Lane. The Principal Investigator, Program Manager, and Author of this study was Mr. G. S. Irons of General Electric.

Acknowledgement is given to Mr. H. Koven , T700 Design Engineering and Mr. P. J. Wessels, Manufacturing Engineer, both of the General Electric Company, and to Mr. R. S. Jakus, Product Engineer at Misco Division of Howmet Corporation, all of whom contributed to the success of the overall program.

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INTRODUCTION

All of the advanced aircraft engines currently being developed by the General Electric Company, Aircraft Engine Group, use highly alloyed, gamma prime strengthened superalloys for the major hot rotating turbine components. The alloys of major interest for equiaxed turbine blades within General Electric are René 80 and René 125. While these alloys offer remarkable properties at elevated temperatures, the design of modern gas turbine engines requires that the gas generator turbine blades be cooled by various techniques. Usual practice is to cast the internal cooling passages where possible. When limited by such factors as section thickness and hole size, cast cooling passages are supplemented with machined cooling holes.

Coring techniques developed over the past years for large thin-walled turbine blades have relied upon single-piece injection molded ceramic core bodies with intricate cooling features such as turbulating bumps, serpentine passages, and oval trailing-edge chordwise bleed holes. Small cooled turbine blades on the other hand have been constrained by the state of the art in ceramic core technology, which has limited the core sizes and configurations that are available to the design engineer. In many cases, the smaller blades have utilized bent quartz rods to obtain small diameter radial convection cooling passages that were not possible to core with ceramic material. The shape of these passages, however, has been limited to uniform cross sections that can be extruded as a hollow or solid rod. Consequently, small cooled turbine blades do not have the more efficient and more intricate cooling schemes which can be incorporated in the larger thin-walled blades.

The objective of this program was to develop an advanced core technology for small air-cooled turbine blades. This technology would allow the application of improved cooling schemes to the T700 first-stage turbine blade. Resulting payoffs would be reduced cost of coring materials and more efficient utilization of cooling air flow, which could be traded off to increased blade life or improved specific fuel consumption (SFC).

BLADE DESIGN

The original T700 stage-one blade design specified eight radial cooling holes. Six of the mid-chord holes were round with diameters of .018 inch, while the leading-edge hole was a .034 inch diameter. The trailing-edge hole was a .063 X .039 inch oval (race track) shape. This hole is the manifold into which the chordwise trailing-edge holes are drilled during the blade machining operations. As a matter of reference, the total length of the T700 blade is 1.25 inches with a chord width of .80 inches and an airfoil length of about .70 inches. This design was used for the first development engines only and was replaced by a more efficient design for the production phase of the T700 engine program. The production blade was selected for application of the advanced coring technology program such that any advances or improvements could then be incorporated into the production program. Basically the production blade did not differ greatly from the development version; however, the improvements made were significant in decreasing manufacturing cost, improving cooling effectiveness, and reducing core complexity. Improved features of the production configuration were the addition of another .018 inch diameter mid-chord hole for a total of seven, elimination of the stepped mid-chord cores, and substitution of the oval trailing-edge hole with a conical-shaped hole placed closer to the trailing edge. The leading-edge hole remained the same. Calculations predicted that the new blade would have improved life over the development blade and this was substantiated by actual engine testing.

Based upon the new production blade design, a program was initiated to incorporate advanced coring technology to improve cooling air effectiveness and to reduce manufacturing cost. After some discussion with turbine airfoil designers, heat transfer analysts, and casting engineers, the following changes were agreed upon for incorporation in the advanced stage-one blade design:

- Turbulated leading-edge oval-shaped hole
- Two serpentine (S-shaped) mid-chord holes

No other changes were to be made in the configuration of the blade; however, a ceramic core tool was to be made to investigate injection molding of the conical trailing edge. A schematic of the evolved design is shown in Figure 1.

Heat Transfer Analysis

Based upon the proposed cooling design shown in Figure 1, a heat transfer analysis was conducted using computer programs developed for previous stage-one designs and modified as necessary to accommodate the new design. Requirements for the analysis were as follows:

- No change in aerodynamics over production design
- No change in outer airfoil and shank configuration
- Same maximum blade inlet temperature

Based upon the above requirements, a steady-state two-dimensional thermal analysis was conducted for the advanced core technology blade. The operating conditions used for the thermal analysis were rated power with 30° F margin added to the turbine inlet temperature and the most recent combustion profile. Calculations were done at 45% span. The resultant metal temperature distribution is shown in Figure 2. A more detailed distribution may be obtained by using the nodal diagram of Figure 3 along with the temperature listings in Table I. The temperature levels shown for the advanced design are, in general, comparable to those for the production blade. However, the advanced blade uses somewhat less cooling air to obtain the equivalent cooling. The turbulated leading edge uses 17% less air and the two serpentine midchord passages use 22% less air for an overall savings of about 12% cooling air when compared with the production blade at the same conditions.

Material Selection

The specified material for all of the T700 high-pressure turbine blades has been René 125, a highly alloyed gamma prime strengthened nickel-base superalloy. This alloy contains a small percentage of hafnium, which improves grain boundary strength at elevated temperatures and also improves castability. No problems have been encountered with this alloy to date in the T700 program and, consequently, René 125 was a natural selection for use in the advanced core technology blade.

Stress Rupture Analysis

A stress rupture analysis was conducted for the advanced core technology blade in Rene 125 and compared with previous data for the T700 production stage-one blade configuration.

Temperature of the advanced blade was as shown in Figure 3 and Table 1. These temperatures were matched to a production blade model at 45% span height and run with an existing computer program. The purpose of this analysis was to assess the rupture life of the new design at both the leading and trailing edges. The rupture analysis represents a first estimate of life and accounts only for the effect of temperature on the rupture life. Calculated findings are summarized in Table 2 and show a small improvement in rupture life for the advanced core technology blade over the standard production design. This difference can be attributed to a slightly cooler leading-edge and a different mid-chord temperature profile.

Design Considerations

Two areas of concern were identified by design engineering about features of the advanced core technology blade. One of these was the potential for small dust particles plugging the serpentine holes at the S-bend near the tip of the blade. The other area was the feeling that the blade tips may get too hot in the mid-chord region.

Plugging of small cooling holes in turbine blades can be a problem, particularly for helicopter operation in dusty environments such as deserts, beaches, or unfinished landing strip areas. As a result, cooling passage design must eliminate any areas from which dust particles cannot be centrifuged out of the tip of the blade by wheel rotation forces. Consequently, small-diameter (approximately .012 inch) dust holes are added to plenums at the tip of the blade for this purpose. This feature can be seen in Figure 1 as a portion of the trailing-edge conical plenum as well as the two serpentine mid-chord passages. In the case of the serpentine passages the dust hole is placed at the top of the S-bend in the tip where the bulk of the airflow is redirected toward the shank of the blade. As a result of the reversed flow conditions, it is uncertain in this case whether the dust particles will be adequately centrifuged through the small hole or whether they will collect and eventually plug the mid-chord hole. Enlarging the diameter to get better dust removal defeats the purpose of the serpentine core in that cooling air loss through the larger hole would be excessive. Therefore, it has been recognized that the S-bend feature is a potential dust trap in actual engine operation.

The other area of concern is for the blade tip which may get too hot in the mid-chord region. The serpentine bends are .125 inch away from the tip, which leaves a large area uncooled except for two small diameter dust holes and two large radial holes. As a basis for comparison,

the production blade has a total of seven radial holes in the mid-chord tip at a uniform spacing, which provides considerable cooling effect. The exact effect of these features cannot be analyzed with any certainty due to the unknown flow conditions and boundary layers in the tip region. Consequently, the effects of this design can only be verified by actual engine test.

CORE MANUFACTURE

The following sections detail the manufacturing approach for the specialized core shapes required for the advanced core technology blade.

Turbulated Leading-Edge Core

As discussed previously, injected ceramic cores can be made to induce turbulation quite easily through incorporation of that feature in the injection die tooling. Quartz cores on the other hand are extruded, not injected, and therefore cannot be manufactured with discontinuities such as turbulating ribs, slots, or bumps. It was quite obvious at the onset of the program that some secondary machining operation would have to be applied to an extruded quartz rod in order to achieve the desired configuration. Two processes were identified for this purpose, i.e., conventional grinding of quartz and the use of a laser beam to vaporize the quartz material. Of the two processes, it was felt that laser machining would be the best due to the zero tool pressure of the light beam, which would not break the fragile quartz rod as readily as a conventional machining operation. However, it was decided to produce samples using both methods and pick the best one to produce the final cores.

Samples of laser machined quartz rods were produced by a vendor using a CO_2 continuous wave laser. Quartz rods were placed on an alumina sheet as shown in Figure 4 and grooves cut in the rods using two techniques to get different depth-to-width ratios. Grooves were cut at a .050-inch pitch to a depth of .003 inch and a width of .007 inch in one pass of the laser beam. Two passes produced grooves with a depth of .005 inch and a width of .008 inch at the same pitch. Sample castings were produced using both types of grooves, sectioned for evaluation and examined metallographically. Figure 5 shows a view of a casting "skinned back" to reveal the turbulating bumps within the leading-edge passage produced with the laser machined quartz rods. A metallographic cross-section taken through one of the turbulators is shown in Figure 6. Evaluation of the cast samples by engineering resulted in the conclusion that the turbulators were not sharp enough to restart the boundary layer film. Consequently, the laser machined samples were not adequate to meet the desired requirements. Discussions with the laser machining vendor indicated that the laser was incapable of producing a very sharp, narrow groove with sharp corners that could produce a cast turbulator meeting design intent. Further work with laser machining was felt to be nonproductive and was discontinued at that point.

Fortunately, the parallel effort to look at conventional machining was proceeding on schedule. Quartz rods were produced with different width grooves machined by grinding with special thin abrasive wheels. Grooves were cut with widths of .005, .010 and .015 inch by .011 inch deep at a .050-inch pitch. No problems were encountered with breakage of the quartz rods and the core vendor was able to produce grooves with widths and depths as specified. Sample castings were made using the machined cores and evaluated the same as those produced with laser cut cores. Figure 7 shows the "skinned back" leading edge of a stage-one blade with three different width turbulators cast within the cored passage. Metallographic evaluation of the cast turbulators as illustrated in Figure 8 showed that the desirable sharp corners could be attained with this method.

Based upon the results illustrated in Figure 8, it was decided to specify machine ground turbulators to the double cut configuration shown in Figure 9. This view was added to the advanced core technology drawing where 12 turbulating fins at a pitch of .050 inch are specified at the leading edge of the first cored passage. Slot width is required to be .0110/.0085 inch. Special tooling was provided to the core vendor to produce this desired configuration. As a direct result of the sample evaluation phase and provision for special tooling, very few problems were encountered in producing cores to the blueprint requirements for the engine test hardware.

Serpentine Mid-Chord Core

Manufacture of the S-shape serpentine mid-chord cores required that two 180° bends be made in small-diameter quartz rods. This requirement was new in that rods are normally bent only a few degrees in order to transition from the blade shank into the airfoil. One main consideration in heating and bending quartz is to avoid stretching the bend area and producing a necked down cross-section at the bend point which can reduce airflow. Sample S-bent cores were obtained from the casting vendor using soft tooling. These samples were found to be necked down substantially to a cross-section which was 22% less than that of the rod. This reduction in area did not meet the airflow design criteria of 15% maximum on bend reduction.

Conversations were held with the casting vendor and the core vendor to resolve the bend area reduction problem. More tooling was provided and more samples made of the serpentine bent cores. After several iterations, a method was found which minimized the tensile stresses on the rod at the bend point, thereby minimizing the reduction

in area. A sample core produced in this fashion is shown in Figure 10. Actual measurement of this and similar cores showed the reduction of area to be less than 7%, which more than met the design goal of 15%. Based on the suitability of the samples, the serpentine mid-chord design was added to the engineering drawing and released for production of engine test hardware.

Some discussions were held regarding the required dust hole at the top of the S-bend in the blade tip. One manufacturing alternative was to weld a small-diameter quartz rod to the serpentine core at this point. However this was found to present two distinct problems as follows:

- Further reduction in area at the bend-weld transition point
- Difficulty in placement of core within wax pattern without breaking the dust hole core

Consequently, it was decided to machine the small-diameter dust hole in by electrical discharge machining (EDM) rather than core it into the blade.

Conical Trailing-Edge Core

The conical trailing-edge hole specified for the production blade design is cored using a tapered machine ground quartz rod with a small-diameter dust hole core welded at the tip. This is an expensive core in relation to the cost of a straight radial rod core and represents a cost increase factor of about 10X. One purpose of the advanced core technology blade program was to look at the feasibility of using an injection molded ceramic core instead of the machined quartz core described above in order to reduce manufacturing cost.

A special injection core die was ordered from a tool vendor to produce the conical core. This tool was provided to the General Electric Investment Casting Operation in Albuquerque, New Mexico. Ceramic cores were manufactured using core mixes, injection molding equipment and ceramic core technology already in place at this facility. However, it is necessary to point out that no experience had been accumulated with small-diameter cores such as the T700 conical shape. Consequently, some concern was felt as to whether the small core could be injected, handled, and fired successfully. Surprisingly, the small cores could be transfer molded using a silicone-fused silica core mix and were successfully fired using setter molds to the desired shape as shown in Figure 11. However, yield problems developed with excessive breakage

of the small-diameter dust hole core, such that it became apparent that this feature could not be made as an integral part of the conical core. Analysis of the injected cores using a scanning electron microscope (SEM) showed particle segregation occurring in the small core. As a result of this segregation, the small-diameter core was primarily a silicone binder containing very few silica particles. Consequently, the fired strength of this portion of the core was poor and substantial shrinkage was taking place. It is possible that a modified core mix containing large size fractions of small silica particles and fewer big particles could produce increased strength small-diameter ceramic cores. However, it was not a portion of the advanced core technology program to investigate such alternate core mixes and no further work was done in this area.

Two techniques were tried in order to overcome the problem of dust hole core breakage. One was an attempt to fuse (or glaze) the surface of the fired core with a high temperature gas flame. The other approach was to place a small-diameter quartz rod in the core die and inject the core mix around the rod. Glazing of ceramic cores did not produce any encouraging results as substantial melting and gas bubbling of the cores occurred. These effects distorted the small cores such that they were not usable for any further purpose. The approach with the most promise was the use of small-diameter quartz rods which could be mechanically trapped in the fired core material as shown by Figure 12. Several dozens of cores were made in this fashion and metal was successfully cast around them without any noticeable breakage or other mechanical and metallurgical problems.

Due to the development nature of the ceramic core, however, this technique was not used for the production of engine test hardware. All conical cores were machined from quartz rods in order to meet the program schedules with minimum risk. It was apparent from the initial work done that there is great potential for cost savings and increased design flexibility in the further development of small injection molded ceramic cores, and it is recommended that additional work be done in this area.

BLADE MANUFACTURE

The following sections detail the tooling approach for the advanced core technology blade, the casting process, the dimensional results obtained on the completed castings, and the machining of the castings to a final configuration.

Tooling Approach

Precision investment casting of airfoil shapes requires the use of metal pattern equipment into which wax is injected to form individual disposable wax patterns. For air-cooled turbine blading, air passage holes are generally formed using integral ceramic core bodies or individual fused quartz tubes. In the case of the T700 high-pressure turbine blades, the required hole sizes are so small that the use of integral ceramic cores has been beyond the state of the art. With the advent of small individual injection molded ceramic shapes, small passages can now be formed using quartz tubes or ceramic shapes. In either case, the small cores must be precisely positioned within the wax patterns in order to maintain minimum wall thicknesses as specified by the applicable part drawing.

Two basic tooling approaches have been developed over the years to address this requirement. The first approach developed involves direct injection of wax over the ceramic cores or the prebent tubes as placed in the core seats of the metal injection die. The second approach involves injection of the wax over pull wires, withdrawal of the wires, and insertion or "stuffing" of the ceramic cores or the prebent quartz tubes into the cavities left by removal of the wires. Both approaches can produce satisfactory results, and selection is generally based upon factors such as complexity of cores, size of cores, and amount of bend in cores.

Based upon prior experience with the T700 stage-one blade, the second approach was chosen for tooling the advanced core technology blade. Special wax tooling for this blade was produced by the same tooling vendor as for previous T700 blade tooling. The tooling package also included special tooling to bend the serpentine mid-chord cores and to machine grind the turbulating slots in the leading-edge cores. As a direct result of previous tool experience and the special samples produced as described under "Core Manufacture", very few problems were encountered in producing the tooling for the advanced core technology blade.

Casting Process and Results

Both the T700 production and the advanced core technology first-stage high-pressure blades were cast using practically identical processes. Waxes were injected as described under "Tooling Approach" with the gate wedge attached to the trailing-edge side of the shank. Wax tree assembly consisted of attaching the gate stubs to a runner bar and tying the runner bars together with a ceramic pour cup. A completed mold tree consisted of four runner bars with eight blades per runner for a total of 32 blades per mold. After completion of mold building, each mold was dewaxed and fired. Preheated molds were individually poured in a conventional over-under vacuum furnace. After cooling, each mold was cleaned, identified, cut off, and processed through the complete foundry finishing cycle.

No problems were encountered in casting the advanced core technology blade. In fact casting yields were better than anticipated, such that the order for engine test hardware was overshipped by the foundry. Two areas of concern were suggested in relation to the serpentine mid-chord holes as follows:

- Tendency of S-bends to distort and produce a thin wall condition
- Difficulty in leaching the quartz material from the S-bend passage

No thin-wall conditions were seen on any of the blades sectioned for evaluation. Additionally, there were no kiss-outs which were associated with core movement as opposed to core breakage. Therefore, it was concluded that the serpentine cores did not move appreciably from their original position. Core removal was done in a normal caustic autoclave and the cycle established for quartz rod removal was doubled. This increase in time was sufficient to remove all core material from the serpentine passages as verified on all castings by water flow inspection.

No problems were encountered in meeting drawing requirements for metallurgical integrity and grain size. Metallographic sections taken through the airfoil and shank of the blade at various locations showed very little shrinkage and a uniform eutectic gamma prime structure. All engine test hardware was 100% fluorescent penetrant and radiographically inspected, with losses being at a bare minimum. Grain size was as shown in Figure 13. Configuration of the advanced core technology

blade tip is shown in Figure 14 as a comparison with the configuration of the as-cast production blade tip. The same comparison is shown for the shank configuration in Figure 15.

As part of the qualification process for each blade design, 15 pieces were cut up and all dimensions were inspected. The inspection results were the basis for a probability study used to assure that future castings can be produced which will meet all dimensional requirements within a 95% probability band. The important result of the probability study was that only twelve relatively small changes would have to be made to the casting drawing or casting tooling to assure that the overall process would produce acceptable parts. Additionally, several dimensions would have to be checked in-process at the foundry to assure adherence to the drawing requirements. Overall, the advanced core technology tooling was very good and was determined to be capable of producing quality blades suitable for engine test with a minimum of deviations from the original drawing.

Machining of Castings

Finished castings to Drawing No. 6035T62P03 were provided by the investment foundry to General Electric in order for machining, coating and inspection operations to be accomplished. A new finished machine print (6039T35) was created to define all finishing operations in order to keep the dust hole EDM operation distinct from the production blade operation sequence. No problems were encountered in this operation for which special tooling was provided. No other unique operations were necessary, thus the advanced core technology blade proceeded through the machine shop on the same process routing followed by the production blades.

Operation sequence involved electrostream drilling of the chordwise trailing-edge bleed holes, tip plenum EDM, and shank grinding. After completion of all machining operations, the blades were polished on the airfoils and water flow inspected to assure that the holes were open. After inspection, the airfoils were coated with an aluminum vapor that is diffused into the base metal to protect the blade from hot corrosion during service. Following coating, the blades were aged, cleaned, polished, shot peened on the machined shank to improve fatigue properties, adjusted for proper airflow, and inspected. These operations are part of the general process sequence for any General Electric airfoil and were not unique to the advanced core technology blade.

QUALIFICATION OF DESIGN

The advanced core technology blade was acceptable for use in the T700 engine on the basis of adherence to the applicable engineering drawings and the similarity to previously tested designs. No component fatigue test was conducted as the outer airfoil configuration had not changed from previous designs and the high cycle fatigue strength of the René 125 alloy material had been adequately established on this and other configurations. Metallographic inspection of airfoil and shank sections showed the blade to be sound and essentially free of microshrinkage. Occasional small pores could be found on any section examined, and were the result of eutectic solidification shrinkage which is quite common in the cast René 125 alloy. This condition is not deleterious and will not affect performance of the blade in service. Radiographic inspection and surface penetrant inspection were done at the foundry on all parts. These operations were also repeated on the machined blades after completion of dovetail grinding and various hole drilling operations. Airflow tests were done on each passage of each blade to assure that the proper cooling airflow rates were being met.

As a result of these inspections, the advanced core technology blades were made available for engine test evaluations on a noninterference basis with other hardware. Due to a heavy test schedule, caused by the need to qualify new sources for the production phase of the T700 program, it was not possible to test the advanced core technology blades for inclusion of test data in this report. A test run of 150 hours has been scheduled for these blades during the Summer of 1978.

COST ANALYSIS

At the start of the advanced core technology program it was understood that the more complex core shapes would cost more money and that any benefit such as improved specific fuel consumption (SFC) would have to be traded off against the added core cost. Some potential for cost reducing the total core package was factored into the program through the inclusion of the injected ceramic core shape. As shown by Table 3, the leading-edge turbulated core adds an estimated $3.24 to the core cost, while the two serpentine mid-chord holes add about $0.29. Thus for the advanced core technology blade with the machined trailing-edge plenum core, a total core cost including an allowance for casting scrap would be $10.80. When the estimated cost of the injected trailing edge core of $2.42 is factored in, the total core package can be reduced to $8.32. This number is only about one dollar greater than the estimated 250th engine cost of the production blade core package. Engine test confirmation of predicted SFC savings would lead to life-cycle cost (LCC) savings which could be much greater than the added core costs. Further cost reduction could be achieved by applying the injection molding method to the leading-edge turbulated core; however, this would require further development to achieve the sharp corners desired by engineering.

As required by contract, engine set core costs are listed in Table 4 at the 250th unit, 3300th average and 4700th average. It is obvious from these figures that the cost differential between the two designs is quite small at the larger production quantities. The numbers are also small in comparison with the total finished blade cost. Consequently, a small change in core cost would have very little effect on eventual finished blade cost, and in the event that LCC savings can be substantiated, would represent an attractive trade-off for future production engines.

CONCLUSIONS

The completed program has successfully demonstrated that advanced cooling schemes can be incorporated into small T700-size high-pressure turbine blades. Engine test results are needed to confirm that actual cooling efficiencies and engine performance have been positively affected by the new cooling design. Injection molding of small ceramic shapes has the potential to reduce cost when compared with machined and bent quartz rods. Further work needs to be done in the area of optimizing ceramic core mix formulations for these small shapes in order to take full advantage of the cost reduction potential.

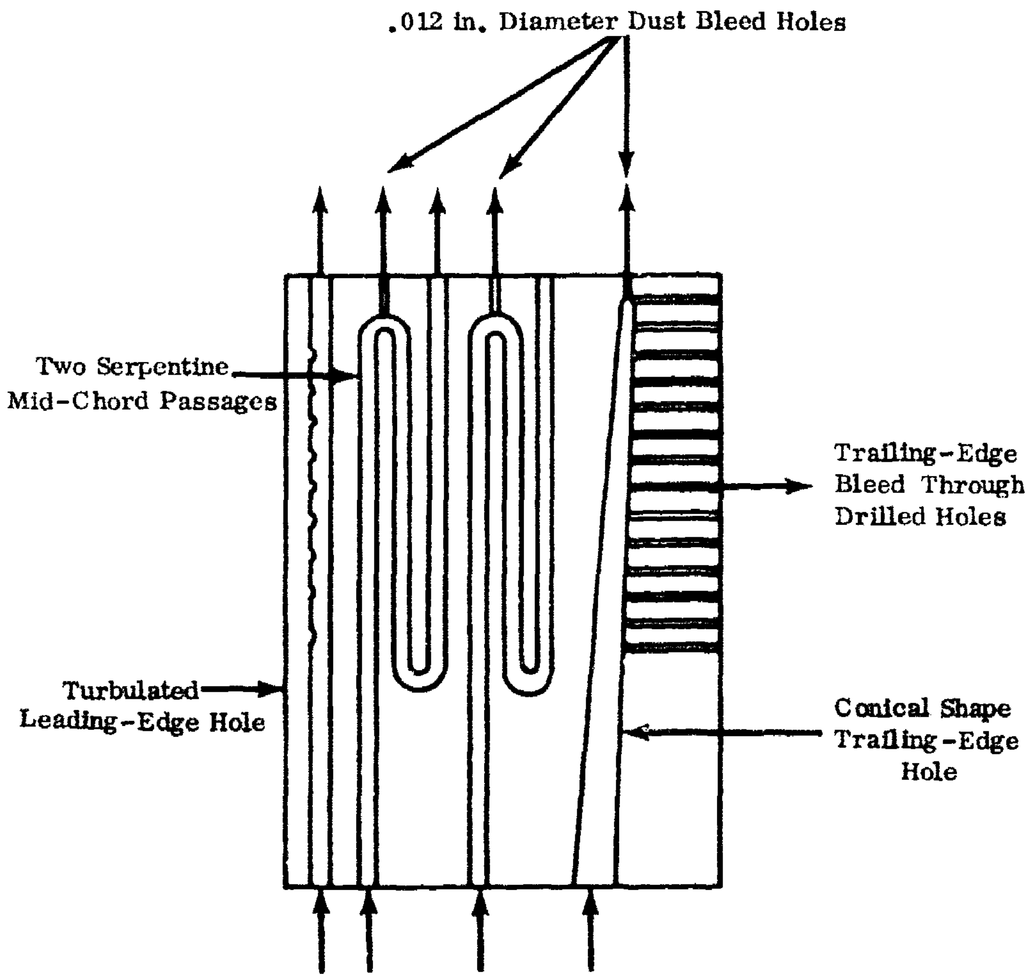


Figure 1. Schematic of Cooling Air Flow Through Advanced Core Technology Stage-One Blade.

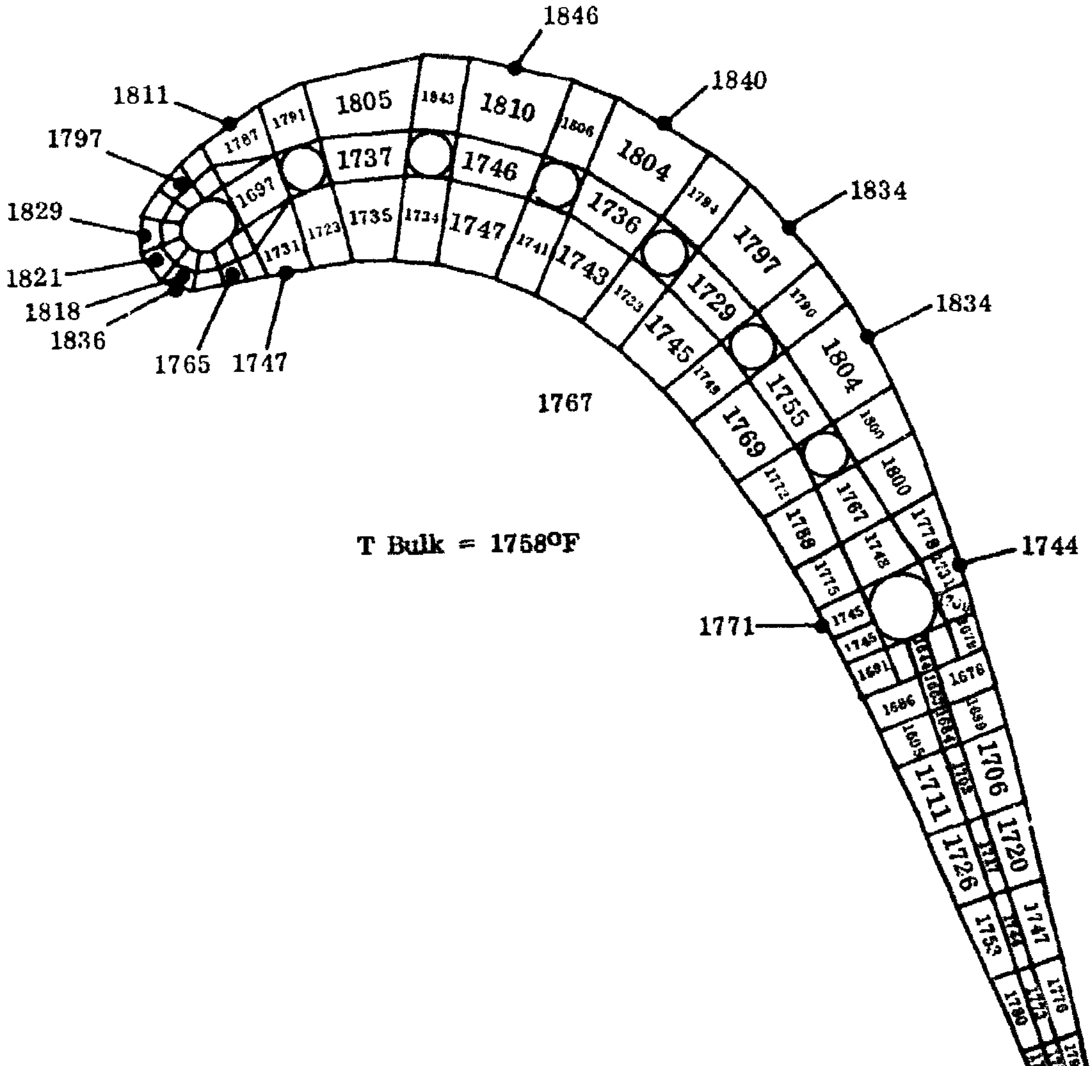


Figure 2. Advanced Core Technology Stage-One Turbine Blade Thermal Profile for 45% Span and Rated Power.

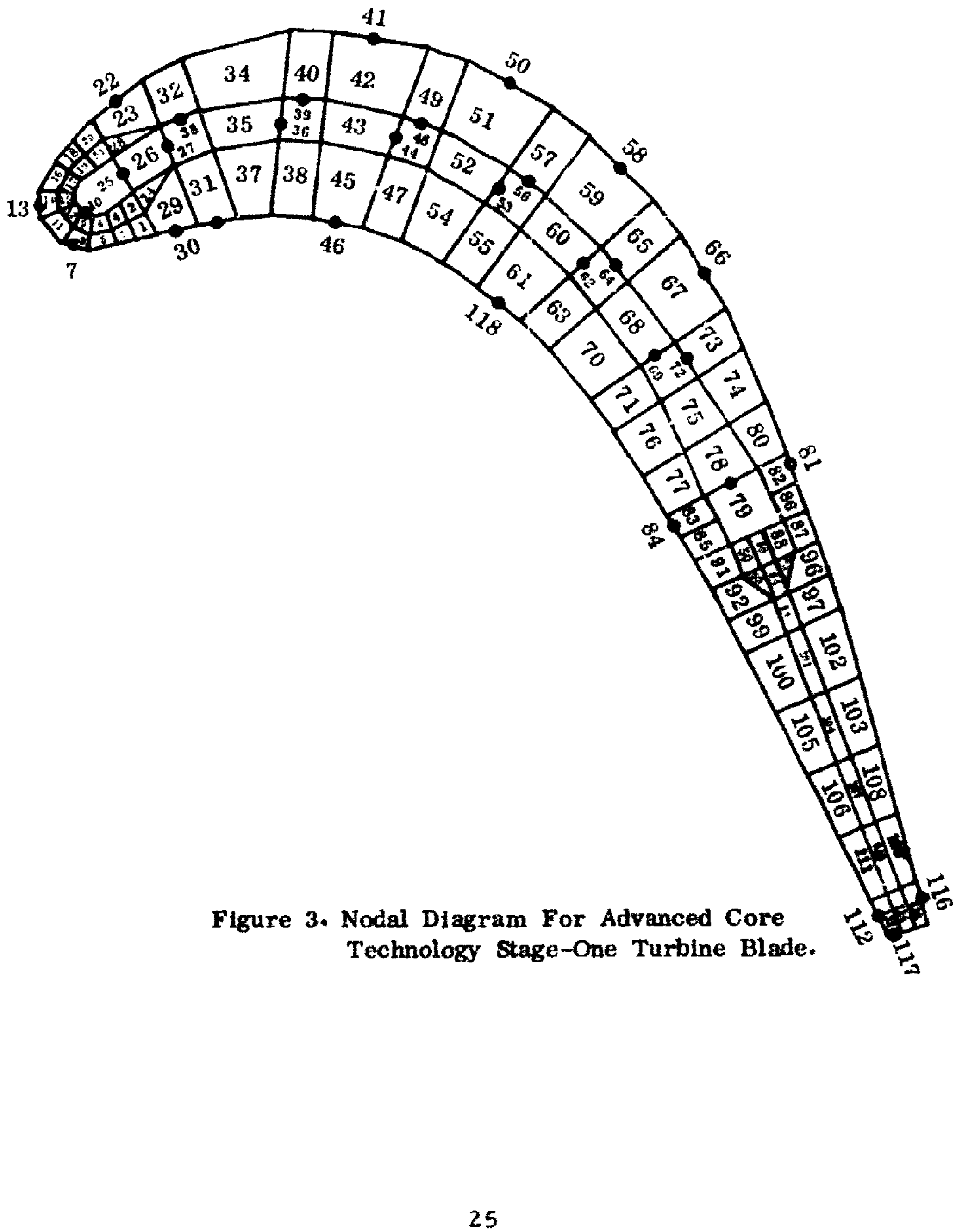
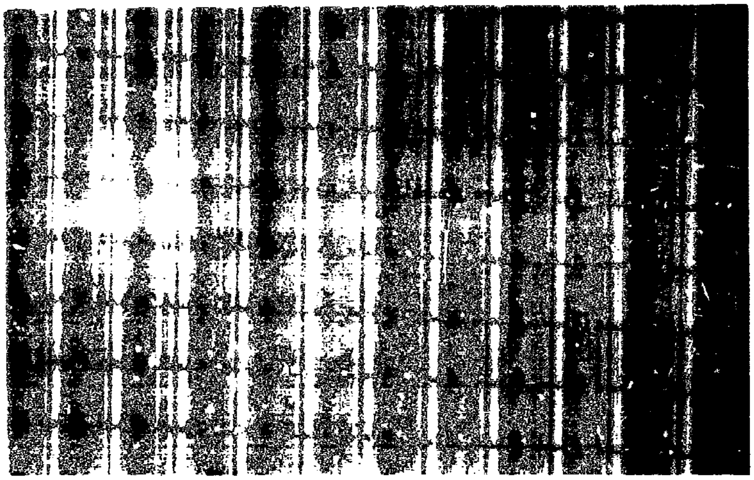


Figure 3. Nodal Diagram For Advanced Core Technology Stage-One Turbine Blade.



(Magnification 5X)

Figure 4. Quartz Rods With Grooves Cut by Laser Beam Machining.

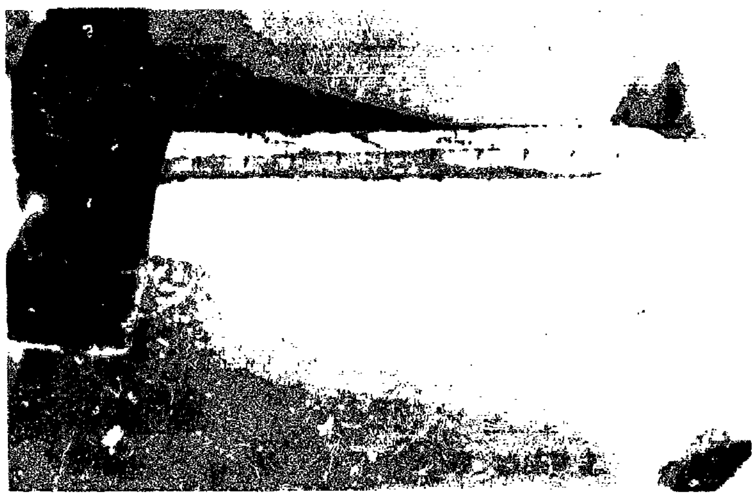


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Figure 5. View of Turbulating Bumps in Leading-Edge Cooling Passage.

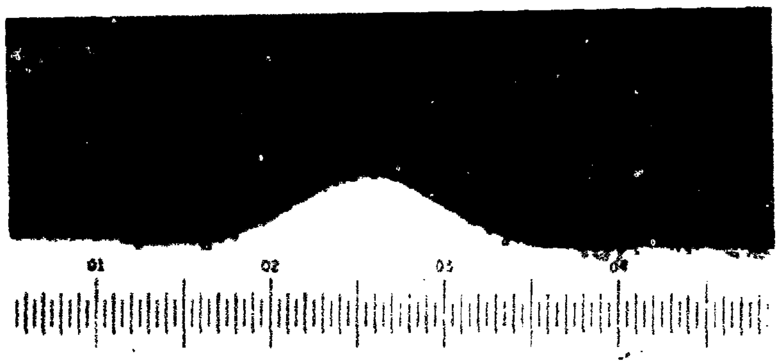

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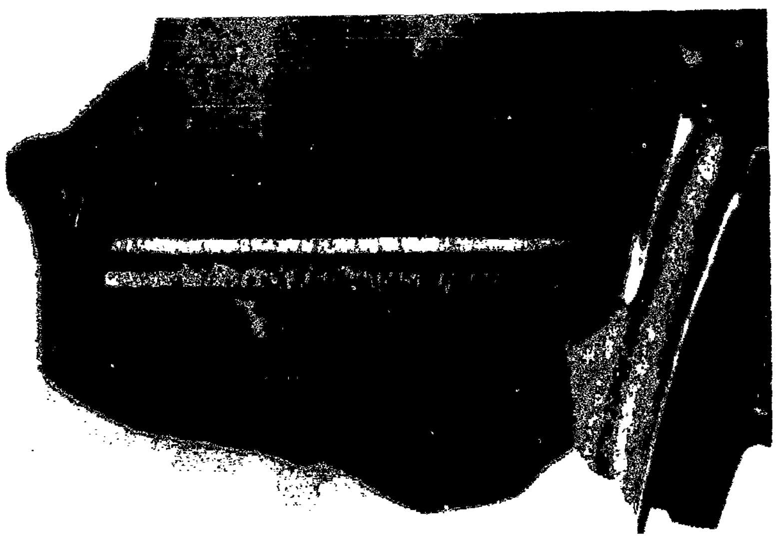
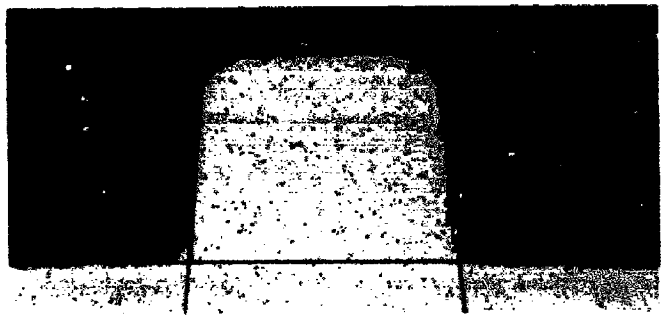
Figure 6. Cross-Section Through Turbulator in Stage-One Blade Casting.

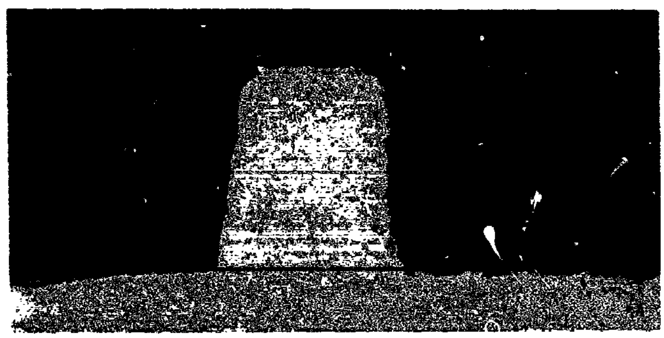


(Magnification 3. 5X)

Figure 7. View of Machine-Ground Turbulating Bumps in Leading-Edge Cooling Passage.



a.) .015 inch wide



b.) .010 inch wide

c.) .005 inch wide

(Magnification 100X)

Figure 8. Cross-Section Through Turbulator in Stage-One Blade Casting.

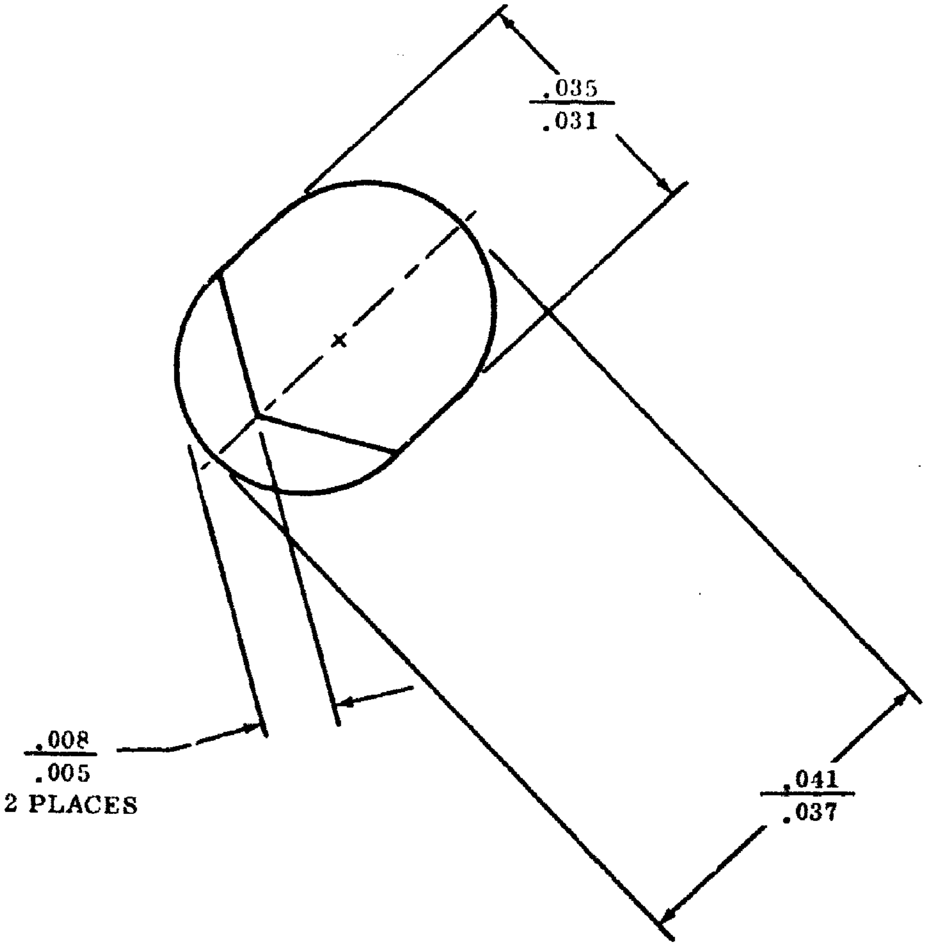
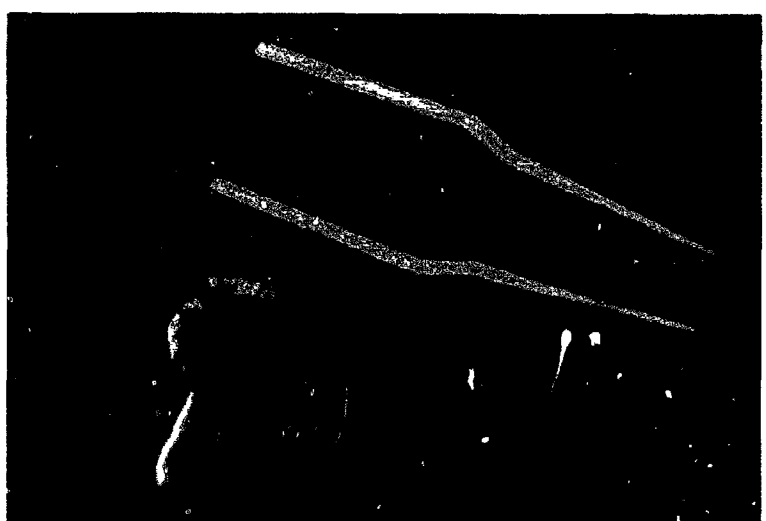


Figure 9. Configuration of Turbulating Rib Specified on Casting Drawing.

(Magnification 27X)

Figure 10. View of 180° Bend in Quartz Rod.

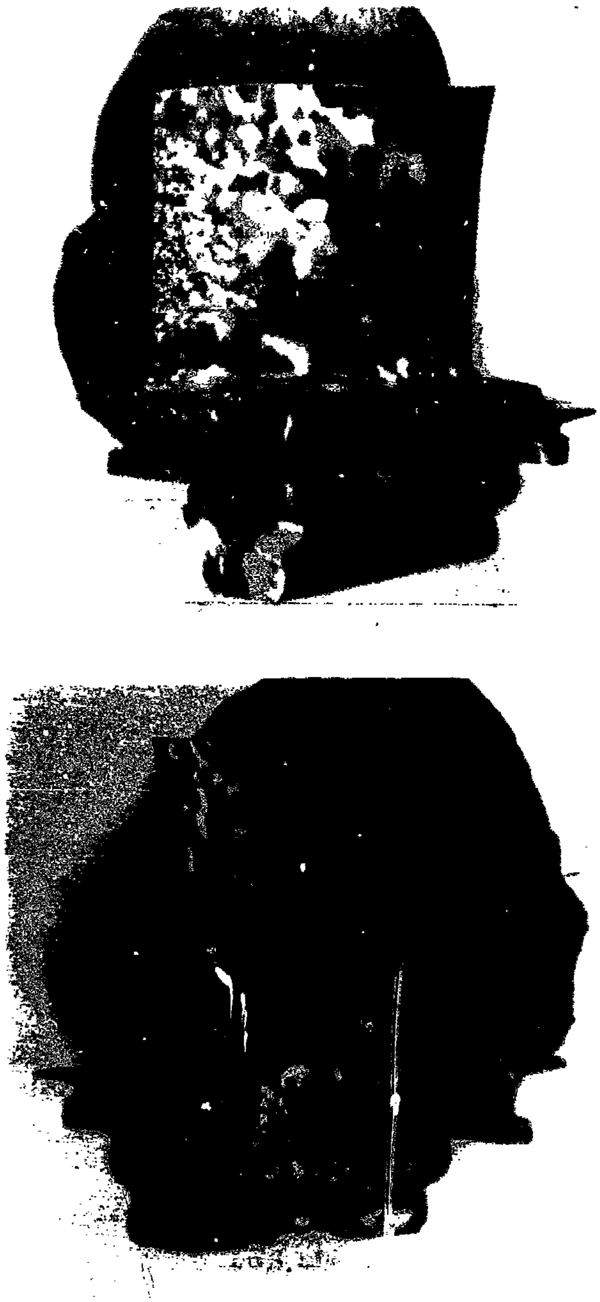


(Magnification 2X)

Figure 11. View of Transfer Molded Ceramic ~~C~~onical Core.

(Magnification 100X)

Figure 12. View of Ceramic Core Material Injection Molded Around Quartz Rod.



Convex
Side

Concave
Side

(Magnification 2.3X)

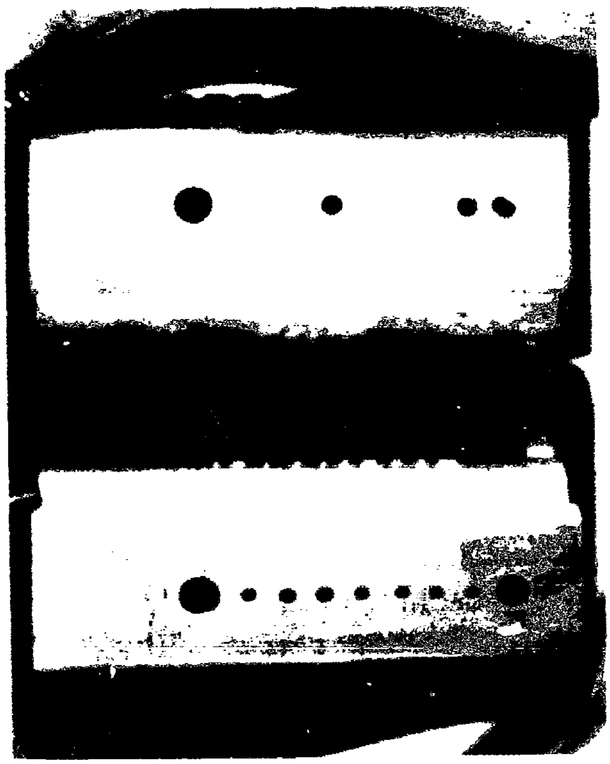
Figure 13. Grain Size of Advanced Core Technology Blade.

Advanced Core Technology Blade

Production Blade

(Magnification 3.7X)

Figure 14. Comparison of As-Cast Blade Tip Configuration.



Advanced Core Technology Blade

Production Blade

(Magnification3. 8X)

Figure 15. Comparison of As-Cast Blade Root Configuration.

TABLE I.

TEMPERATURE VALUES FOR EACH NODE OF ADVANCED CORE TECHNOLOGY BLADE*

NODE	TEMP	NODE	TEMP	NODE	TEMP	NODE	TEMP
1	1751	2	1722	3	1765	4	1733
5	1797	6	1754	7	1836	8	1817
9	1769	10	1727	11	1821	12	1774
13	1623	14	1814	15	1771	16	1803
17	1766	18	1796	19	1764	20	1790
21	1756	22	1810	23	1786	24	1746
25	1650	26	1697	27	1660	28	1717
29	1730	30	1746	31	1723	32	1790
33	1749	34	1804	35	1737	36	1693
37	1735	38	1733	39	1756	40	1803
41	1846	42	1810	43	1746	44	1709
45	1746	46	1771	47	1740	48	1765
49	1805	50	1840	51	1803	52	1735
53	1686	54	1743	55	1732	56	1738
57	1793	58	1834	59	1797	59	1729
61	1745	62	1687	63	1747	64	1750
65	1796	66	1834	67	1803	68	1754
69	1717	70	1769	71	1771	71	1763
73	1800	74	1799	75	1766	76	1788
77	1775	78	1743	79	1717	80	1773
81	1743	82	1730	83	1745	84	1771
85	1721	86	1706	87	1679	88	1649
89	1644	90	1652	91	1690	92	1685
93	1666	94	1662	95	1664	96	1678
97	1689	98	1684	99	1695	100	1710
101	1702	102	1706	103	1720	104	1717
105	1726	106	1752	107	1744	108	1746
109	1775	110	1772	111	1730	112	1808
113	1798	114	1792	115	1795	116	1803
117	1800	118	1766				

*Refer to Figure 3 for Location of Each Node.
All temperatures in °F.

TABLE 2.

SUMMARY OF STRESS RUPTURE LIFE ANALYSIS

	Advanced Blade		Production Blade	
	LE	TE	LE	TE
Node*	(62)	(18)	(62)	(18)
Relaxed Stress, KSI	14.7	10.8	13.5	12.3
Temperature, ^{o}F	1787	1796	1793	1789
Life, hours	1744	458	1370	315

*See Figure 3 and Table 1 for Temperature of Advanced Core Technology Blade.

TABLE 3.

SUMMARY OF CORE COST FOR STAGE-ONE TURBINE BLADES

BLADE DESIGN	CORE CONFIGURATION	COST
Production Blade	Leading-Edge/Bent Rod	0.30
	Mid-Chord/Seven Bent Rods	2.07
	Trailing-Edge/Machined Rod with Bend	4.90
	TOTAL CORE COST/BLADE	$7.27
Advanced Core	Leading-Edge/Turbulated and Bent Oval Rod	3.54
	Mid-Chord/Two Bent Rods	2.36
	Trailing Edge/Injected Ceramic Core with Dust Hole	2.42
	TOTAL CORE COST/BLADE	$8.32

NOTES: Core cost in 1978 year dollars at shop cost.
Casting scrap factor included in core cost.
All costs at 250th engine set.

TABLE 4.

CORE COST PER ENGINE SET OF STAGE-ONE BLADES AT VARIOUS QUANTITIES

BLADE DESIGN	250th UNIT	3300th AVG.	4700th AVG.
Production	$247	$198	$186
Advanced Core	$283	$226	$214

NOTES: Material at shop cost in 1978 year dollars.

Shop cost does not include materials purchasing and handling expense (MP&HE).

Learning curve used is consistent with the design-to-cost procedures established for the T700 and approved by the Army.

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